ULTRASTABLE QUARTZ OSCILLATOR FOR SPACECRAFT

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Abstract

A new series of quartz oscillators that have excellent performance has been developed for use in spacecraft. Some oscillators using this design have demonstrated 24–hour aging rates of less than 1×10^{-11}, 100-s Allan variances of 7×10^{-14}, and a phase–noise floor of -158 dBc.

Variations in resonator performance exceeding factors of 10 have been found during the evaluation of resonators using the same test oscillator; this finding indicates that oscillator performance is still dominated by the quartz resonator. SC cut resonators manufactured by different companies using a variety of mounting techniques and resonator enclosures have been used in this design. Some performance parameters are directly related to resonator type.

The oscillators are designed to survive the rigorous environment of a rocket launch. They are projected to have a minimum useful life of 5 years in a space environment through the use of conservative design margins, high–reliability components, and a rugged mechanical package. A vibration isolation system is incorporated that attenuates the band of frequencies generated by currently available launch vehicles that could potentially damage the oscillator. The oscillators are compact and low weight and have low power consumption.

A dual thermal insulating system using a unique Dewar flask design and a space blanket (alternate layers of a porous spacer and radiation–reflective aluminized Mylar) is used to isolate critical oscillator components from the thermal environment and to reduce power consumption. The design of the Dewar flask, which is made from titanium, requires no pinch–off tubes or other protrusions outside of the basic cylindrical envelope of the Dewar.

A clearly defined frequency versus ambient pressure change was recognized during development of these oscillators. Components used in the oscillator were identified as the main cause of the pressure sensitivity, but after these components were replaced, a pressure sensitivity remained that is related to individual resonators and resonator types.

INTRODUCTION

This paper will present the performance results from a new series of high–performance quartz oscillators developed for use aboard spacecraft. Test results revealed the quartz resonator has a very

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heavy impact on oscillator performance. Design features that make this oscillator well suited for use in spacecraft will be discussed. Finally, measurement results and observations of oscillator frequency versus ambient pressure will be presented.

More than 30 oscillators using the same basic design have been fabricated, and 24 of the oscillators have been spaceflight qualified. A 5–MHz third–overtone SC cut resonator controls the output frequency of the oscillator. The resonator and critical oscillator components are housed in a high–stability single proportionally controlled oven that maintains a constant temperature over the ambient operating temperature range to ensure high performance.

ALLAN VARIANCE AND PHASE–NOISE RESULTS

Table 1 contains data selected to illustrate the performance of some of the best and worst oscillators. The mean 100–s Allan variance for the entire oscillator group is very good, and four of the oscillators (S/N4, S/N10, SC5, and SC7–92) achieved an Allan variance in the 10^{-14} range. Data for the series of oscillators designated by SC7 are particularly interesting. Oscillator SC7 is a test oscillator that was used to evaluate resonators, and the dash following SC7 indicates a specific resonator being evaluated. As shown in Figure 1, the 100–s Allan variance for this group of oscillators (SC7, SC7–2, SC7–92, SC7–10, and SC7–38) varies over a wide range (8×10^{-14} to 1.5×10^{-12}). The only difference between these oscillators is the resonator; therefore, performance must be related to the individual resonator. As a further indication that oscillator performance is dominated by the resonator, oscillators SC8–4 and SC7 used the same resonator and performed similarly (see Figure 2), yet they are very different physically and even use different types of electronic components. The mean Allan variance for the group of oscillators and the Allan variance for two of the best performing oscillators SC5 and SN10 are also presented in Figure 2. The Allan variance for τ of 1000 s is heavily influenced by the oscillator aging. For oscillators that have very low aging rates, such as SC5, there is little difference between the 100– and 1000–s Allan variances. Phase–noise data for the oscillators are also presented in Table 1, and a plot of phase noise is depicted in Figure 3. If the Allan variance and phase–noise data for the same oscillator are compared, tracking between the two is not consistent. Actual phase noise is probably 6 to 10 dB better than presented, particularly below 10 Hz, because of two sources of potential error: (1) a low–phase–noise reference oscillator was not always available for phase–noise testing, and (2) the phase–noise test equipment has an error of 10 to 12 dB below 10 Hz. The phase–noise data presented are on the conservative side. Although the data are known to have some error, the oscillator performance is at least as good as shown. All the data presented in this paper do **not** assume equal noise sources from each oscillator.

Other oscillator performance data are presented in Table 1 without comment except for frequency versus temperature. A design change was implemented, which reduced the temperature coefficient to the mid to low 10^{-13} range per degree Celsius. Resonators from both Bliley Electric and Piezo Crystal have been used in these oscillators; performance from each manufacturer has varied between very good and mediocre.

THERMAL ISOLATION SYSTEM

These oscillators were designed to operate in a space environment where power consumption, size, weight, and the ability to survive the rigors of a rocket launch are always of concern. The method of

providing thermal isolation for the oscillator has a direct influence on these parameters. Glass Dewar flasks have good insulating qualities, but they are bulky, heavy, and fragile. Space blanket or super insulation (alternate layers of a porous spacer and radiation–reflective aluminized Mylar) is extremely efficient but requires a vacuum to be effective. Oscillators at the Applied Physics Laboratory have traditionally used super insulation for thermal isolation; however, requirements for the oscillators to operate at atmospheric pressure have been requested by some of our sponsors. Not being very fond of the penalties imposed by a glass Dewar, we designed the titanium Dewar flask shown in Figure 4, which has very appealing characteristics. The titanium Dewar is light and rugged, has a small cross–sectional area between the walls, and has no pinch–off tubes or other protrusions outside the cylindrical shape of the Dewar. These advantages far outweigh the titanium Dewar's disadvantage of not being as thermally efficient as a glass Dewar. When the titanium Dewar is used in combination with super insulation, a thermal isolation system is realized with a slight increase in size and weight, which permits ground–based operation yet retains the extremely efficient insulation qualities in the vacuum of space.

VIBRATION ISOLATION

A mechanical resonance in the system used to attach the quartz disk to the resonator enclosure will severely damage or destroy the resonator if excited. The frequency of this resonance is in the range of 200 to 1000 Hz. A unique vibration isolation system that is equally effective in all three orthogonal axes is incorporated in the oscillator design to isolate the resonator from the external environment for frequencies above 100 Hz. Figure 5 presents the attenuation characteristics of the isolation system as a function of input excitation frequency. The heart of the system is an elastomeric frustoconical–shaped isolator molded from a low–Q RTV compound. A photograph of the vibration isolation system is shown in Figure 6. By varying the thickness, diameter, and composition of the RTV, the cutoff frequency and attenuation characteristics of the isolator can be tailored to accommodate different weights and vibration profiles. The isolators are carefully processed to eliminate air bubbles during molding and are then baked out in a vacuum to remove volatile components from the molded isolators.

AMBIENT–PRESSURE–INDUCED FREQUENCY CHANGE

During early development of this oscillator, a slow varying frequency change was observed that did not seem related to any known cause. The character of the frequency change suggested it would be related to temperature. Ambient temperature and frequency were monitored, and little correlation was observed between the two. A second oven was added to a test oscillator, but the frequency wander persisted. The frequency wander does not occur during oscillator evaluation in a vacuum that simulates a space environment. After observing the oscillators for several months, the frequency changes in air seemed to be related to weather–front movements. When the atmospheric pressure was recorded and compared with the oscillator frequency changes, correlation between the two was quite good, as shown in Figure 7. Two of the oscillators, SC5 and SC11, have a negative frequency change when the pressure increases, whereas the frequency change of oscillator SC3 is positive with increasing pressure. Figure 8 shows how two oscillators performed during the passage of hurricane Hugo up the East Coast. When pressure increases, frequency changes are larger and the change occurs more rapidly, which may be observed in both Figures 7 and 8. An air dielectric variable piston capacitor used to set the oscillator output frequency was considered to be the most likely component causing

the frequency changes. This capacitor was removed, and indeed the frequency changes were decreased but not eliminated. Tests are continuing to be conducted, but the following observations can be made. The glass–enclosed resonators from Bliley show the largest variation from unit to unit; some have almost no change, whereas others are 10 to 20 times worse. Metal–enclosed resonators from Piezo Crystal have smaller frequency changes than the Bliley units by a factor of 2 to 5; however, only a few samples have been tested. BVA resonators have the best performance, but again the number tested is quite small (< 5).

The size of the oscillator is $5 \times 4 \times 2.2$ in., it weighs 1.7 lb, and it consumes 0.9 W at 27 degrees Celsius.

CONCLUSION

An oscillator has been designed that is well suited to cope with the harsh environment of a rocket launch and the vacuum of space. The oscillator has outstanding performance and perhaps could be even better or at least more consistent if there was a clear understanding of why some quartz resonators perform better than others. This knowledge could then be applied to resonator design and fabrication technology to improve the breed of currently available resonators.

Table 1

SERIAL NO	35 0SC AVERAGE	S/N4	S/N10	SC4	SC5	SC8-4	SC7	SC7-2	SC7-92	SC7-10	SC7-38
Drift Rate/24 Hr	4.1E-11	6E-12	7.5E-11	2E-10	4E-12	2E-11	3E-11	-4E-11	7E-12	1E-10	2E-10
ALLAN VARIANCE											
Tau(Sec)											
0.01					6.2E-12	6.9E-12			1.5E-11		
0.1	5.2E-12	4.6E-12	7.7E-12	2.7E-12	2.1E-12	1.4E-12	1.3E-12	2.3E-12	1.1E-12	1.5E-12	4.8E-12
1	6.5E-13	3.3E-13	6.5E-13	3.1E-13	3.5E-13	4.1E-13	4.9E 13	4.3E-13	1.5E-13	6.1E-13	3.1E-12
10	1.7E-13	1.6E-13	9.8E-14	2.1E-13	8.9E-14	2.2E-13	2.4E-13	2.5E-13	1.2E-13	9.1E-13	4.8E-12
100	1.7E-13	8.9E-14	8.4E-14	2.1E-13	6.6E-14	1.8E-13	1.9E-13	3.4E-13	8.1E-14	1.5E-12	7E-12
1000	9.5E-13	1.4E-13		3.1E-13	7.4E-14	3.1E-13	4.1E-13		3.3E-13		
PHASE NOISE dBc/Hz											
Freq Offset(HZ)											
1	-114.63	-113	-114	112	-121	-110	-114	-111	-122	-109	
10	-138.75	-141	-141	-142	-139	135	-141	-135	-136	-134	
100	-148.25	-147	-148	-152	-147	-147	-153	-145	-147	-144	
1000	-151.00	-149	-150	-153	-150	-152	-154	-147	-153	-147	
10000	-152.63	-150	-150	-155	-152	-154	-157	-147	-156	-147	
100000	-153.25	-149	-150	-155	-152	-156	-157	-147	-160	-148	
Freq as Function of											
Temperature per °C	1.5E-12	2.1E-12	8.6E-13			6.2E-13					
Load	2.4E-12	2E-12	2.7E-12	5E-12	2E-12		7.0E 10	3.8E-10			
Voltage	2.0E-12	1E-12	3E-12					<1E-12			
Output Characteristics											
Voltage Level	1.55	1.38	1.5	2.1	1.5	1.18	1.9		1.89		
Harmonic (dBc)	-62	-62	<-60	-45	-48				-63		
Spurious (dBc)	-77	-72	<-80								

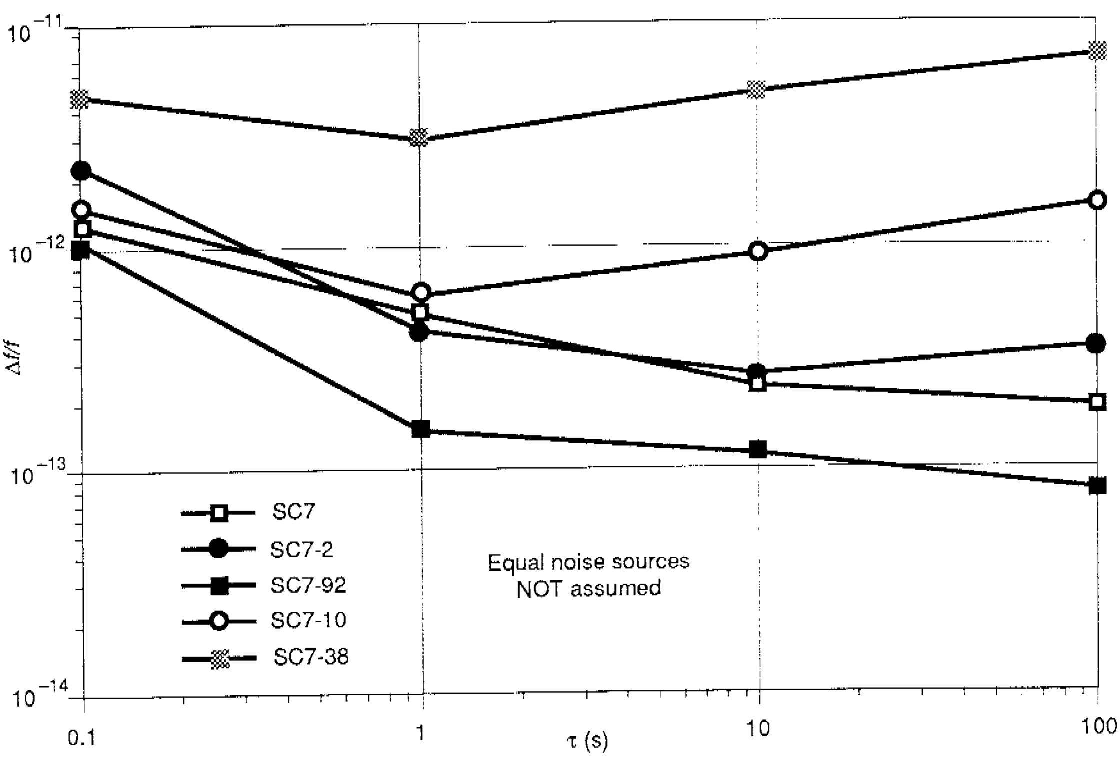

Figure 1. Allan variance of oscillator SC7.

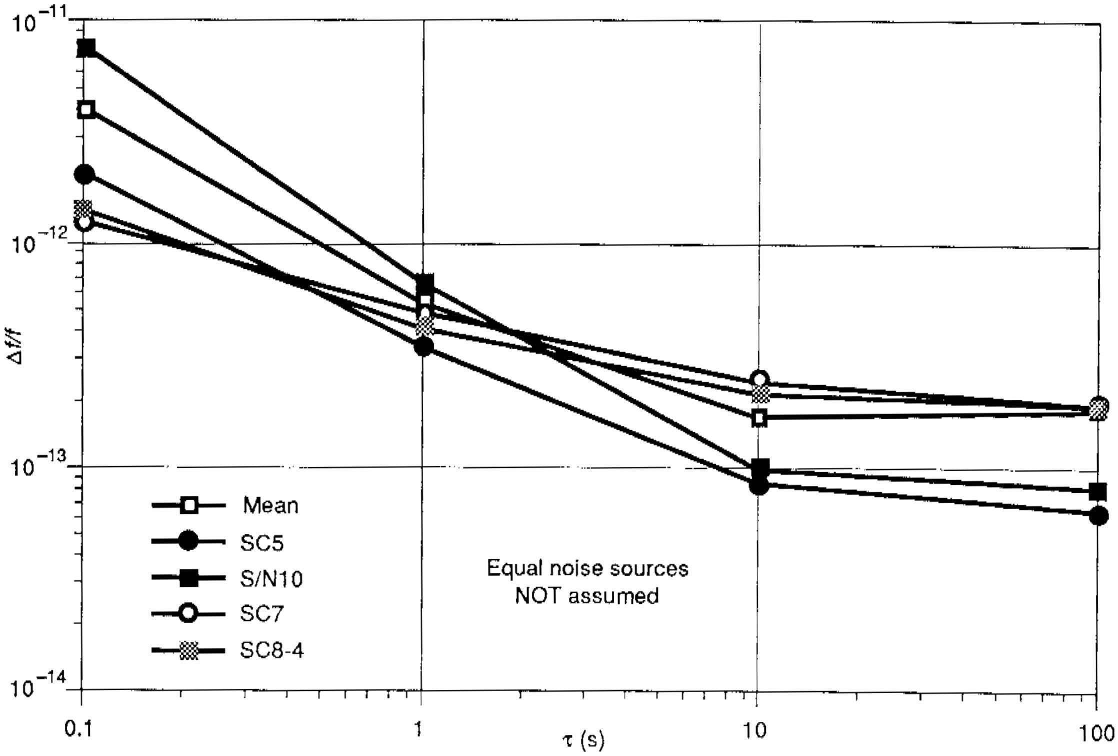

Figure 2. Allan variance of selected oscillators.

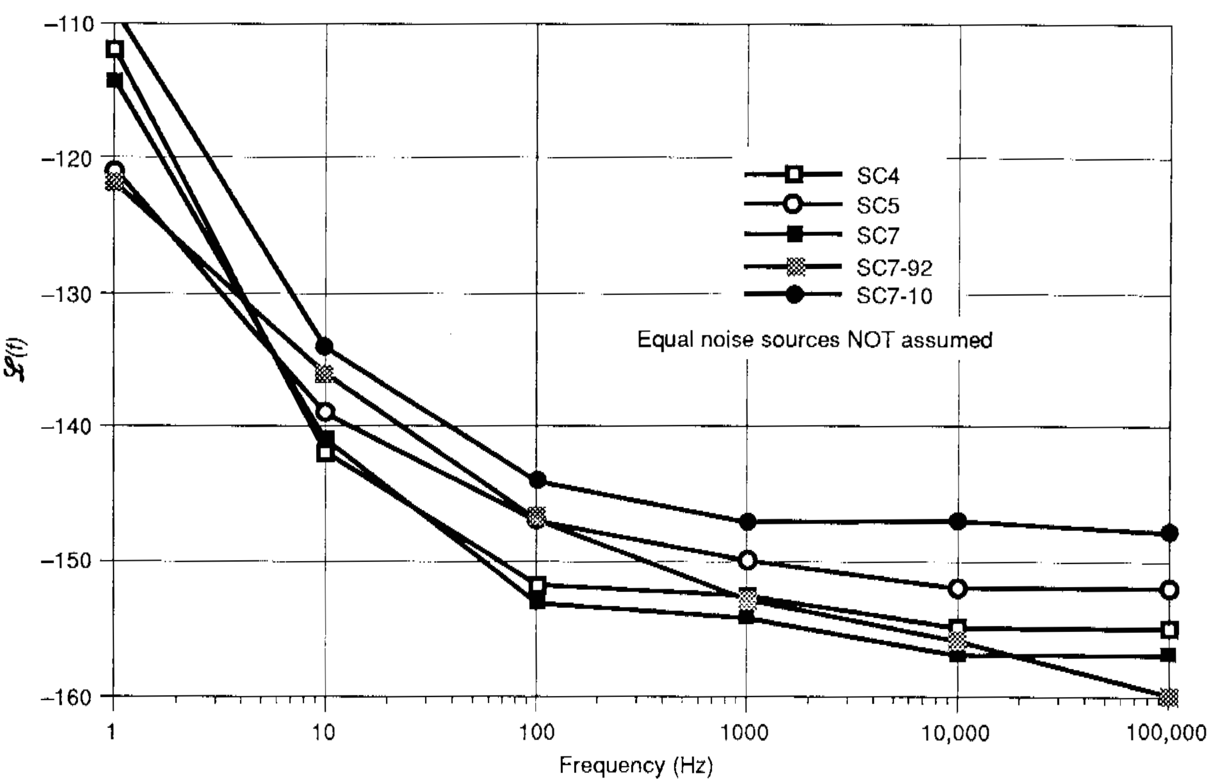

Figure 3. Phase noise of selected oscillators.

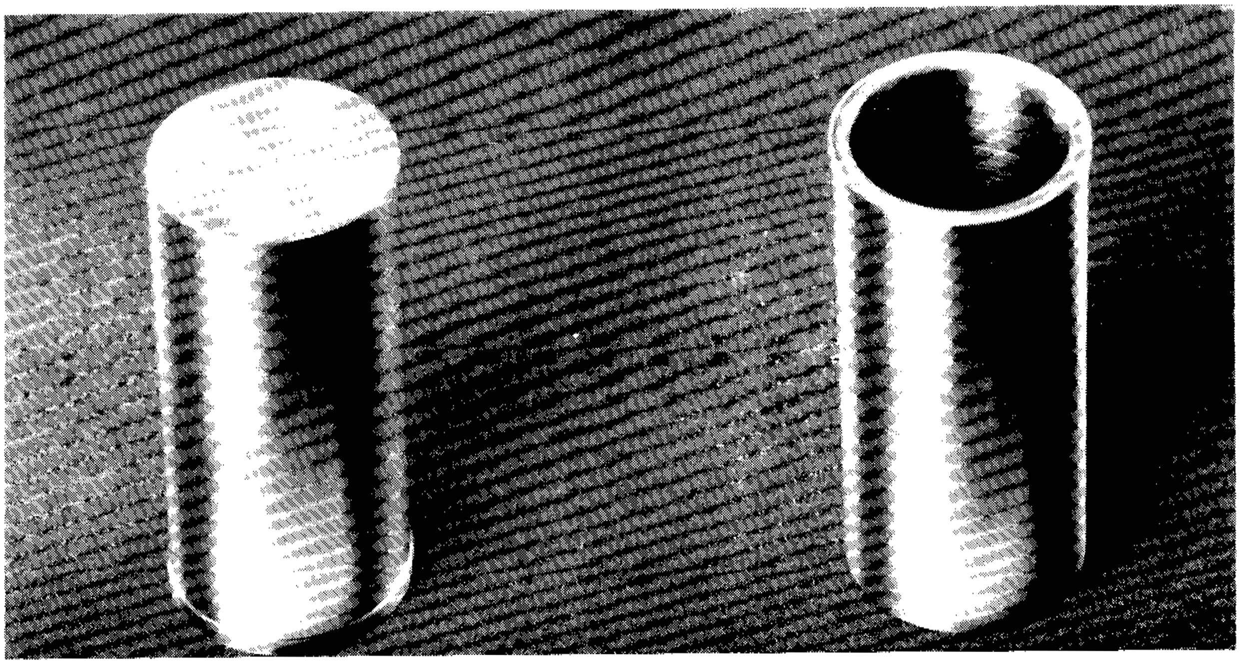

Figure 4.   Dewer flask.

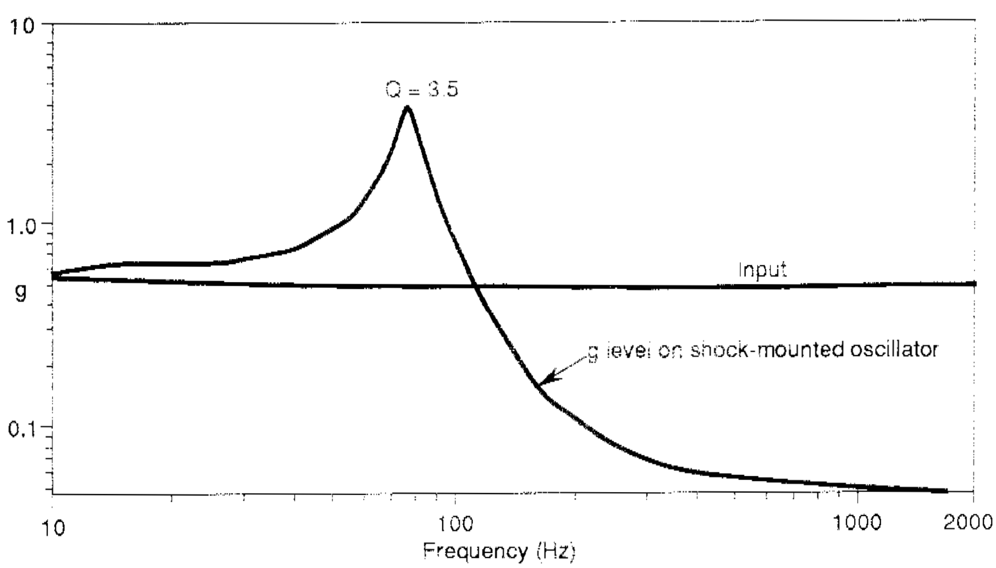

Figure 5.   Attenuation characteristics of the isolation system as a function of input excitation frequency.

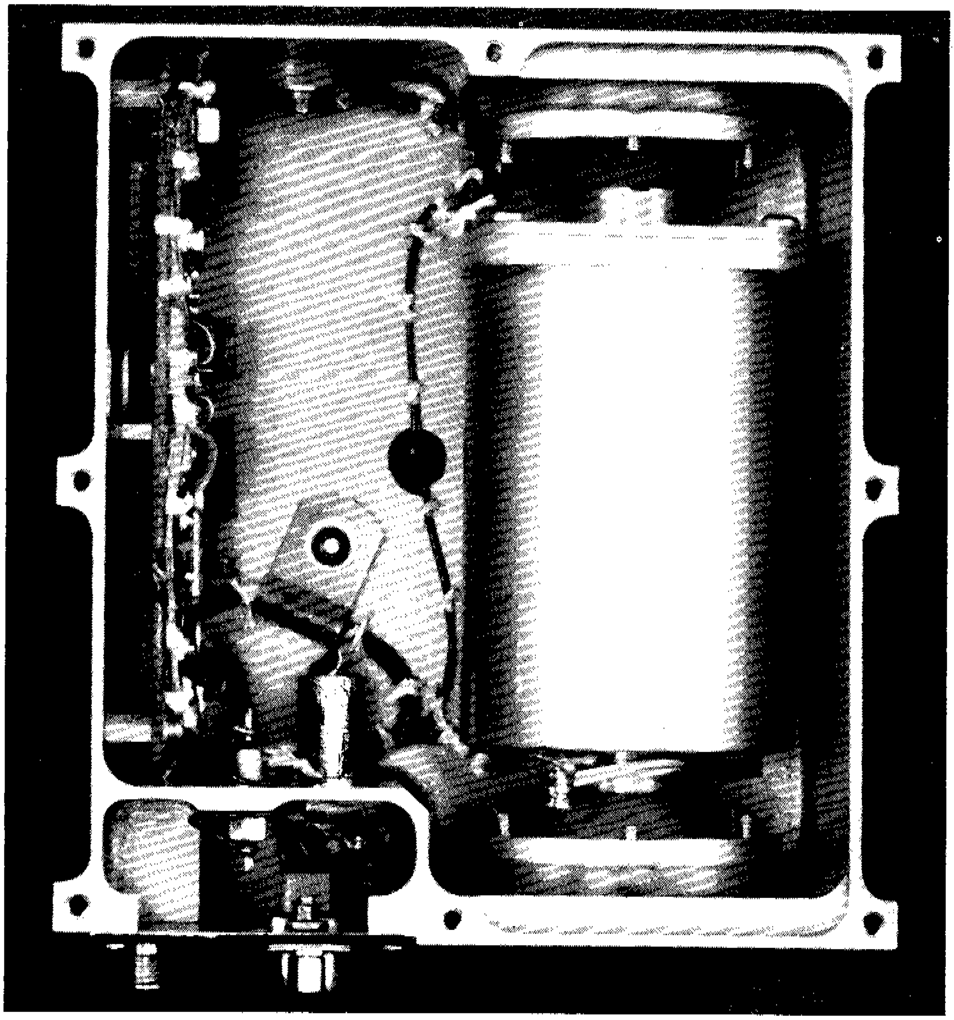

Figure 6. Vibration isolation system.

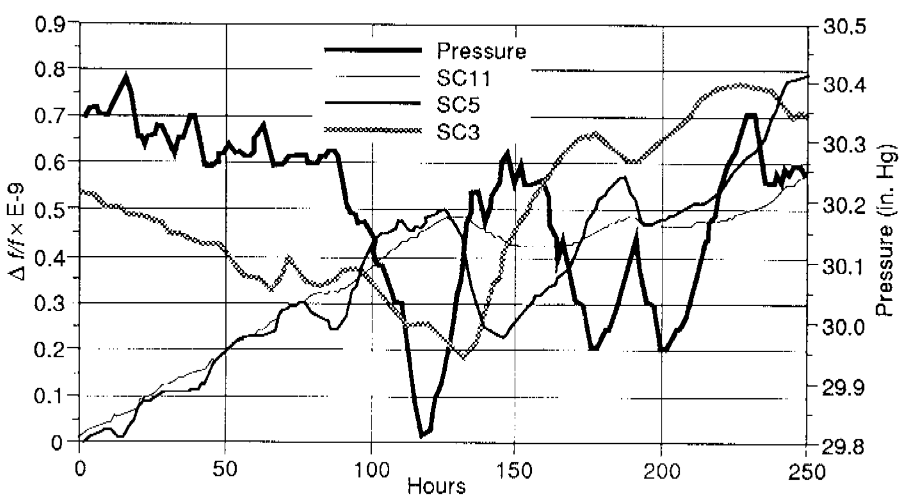

Figure 7. Oscillator SC3, SC5, and SC11 pressure-induced frequency change.

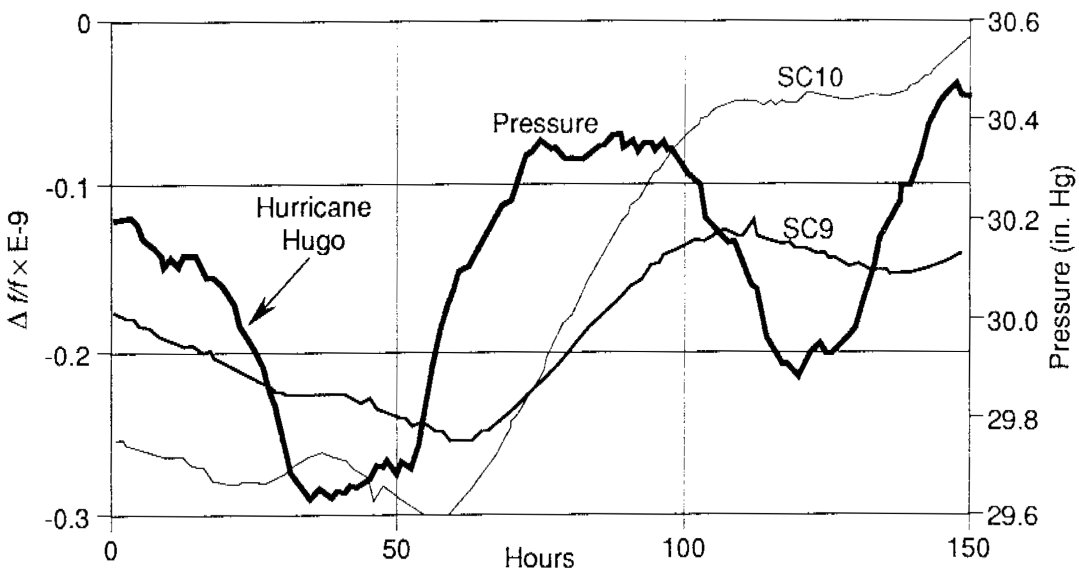

Figure 8. Oscillator SC9 and SC10 pressure-induced frequency change.

QUESTIONS AND ANSWERS

FRED WALLS, NIST: Of the oscillators that reach $\approx 7 \times 10^{-14}/$, were they just SC cut? Could you comment as to whether they were fifth overtone SC's or what?

MR. NORTON: All the resonators used for this paper were third overtone SC's, 5 MHz. We use resonators from two different manufacturers with at least three different mounting techniques. The oven is a single proportional oven. Is there anything else that you want to know?

MR. WALLS: You are one of the few people that have seen many oscillators drop below 1×10^{-13} and obviously some of your circuit design makes quite a difference. Would you care to comment on what is special about your circuit?

MR. NORTON: To be honest, the is nothing extremely special about it. It is a modified Colpitts oscillator. We have a fairly heavy copper oven which probably helps with the thermal problems. We think that we have a pretty good oven design, which certainly contributes to the overall performance. The measurements in parts in ten to the 14^{14} are not isolated cases. Those are not something that we see once or twice. When the barometric pressure is nice and stable, we see 3 and 5 in ten to the fourteenth for short periods of time. I might mention that the frequency wander that we see—these are spacecraft oscillators and we do qualify them in a thermal vacuum system. Once they get in there, that frequency wander goes away so I think that it would be important to seal oscillators if you were building oscillators for ground based operation.

MR. WALLS: I guess that I would agree with that. It is not just pressure but I believe that humidity plays quite a role. Those that have been hermetically sealed seem to perform substantially better.

MR. NORTON: We haven't run any tests with humidity, but when you get weather front changes you get humidity changes. The environment that these oscillators are tested in is a dual air conditioning system so that, while the humidity is not constant, it doesn't change very rapidly or very far. I would agree that humidity contributes something to it also.

MR. WINKLER: I am going to ask you where the pressure was measured. The reason for the question is that there is a world–wide diurnal cycle which one can see everywhere. I couldn't see that on your data. The suspicion is that it was measured inside some sort of vessel or inside the laboratory.

MR. NORTON: Obviously it is inside a building. The pressure was measured inside the same enclosure with a recording barometer which is capable of measuring to a one/hundredth of an inch of mercury. The barometer and the device under test were separated by 6→8 feet.

MR. WINKLER: It is still strange that one does not see the diurnal effect.

MR. NORTON: Remember that that was for very short intervals, a couple of hundred hours. If you are concerned about the pressure measurements—we are located about 20 miles from BWI, the Baltimore–Washington International airport. We have correlated our data with data from the airport, so I don't think that we have a problem as far as pressure measurements are concerned.

UNIDENTIFIED QUESTIONER: In the oscillator circuit, is the crystal dissipation controlled by self–limiting, or an automatic gain control circuit?

MR. NORTON: It is an automatic gain control circuit.